

Preparation and Performance Analysis of Epoxy Resin Thermal Conductive Insulating Composite Materials

Chunxue Song^{1,*}, Xiangqing Wang¹, Yupeng Chen², Feng Wang³

¹ School of Pharmacy, North China University of Science and Technology Tangshan, Hebei, 063210, China

² School of Metallurgy and Energy, North China University of Science and Technology, Tangshan, Hebei, 063210, China

³ School of Materials Science and Engineering, North China University of Science and Technology, Tangshan, Hebei, 063210, China

*Corresponding Author: Chunxue Song

Abstract

The article primarily summarizes and introduces the key technologies and development trends of epoxy resin thermal conductive insulating composite materials. It begins by outlining the preparation methods of such composite materials, with a focus on critical factors influencing their thermal conductivity and strategies for optimizing the preparation process. It then analyzes the selection of thermal conductive fillers in these materials and their roles in enhancing thermal conductivity and insulation performance. Furthermore, it elaborates on specific applications of epoxy resin thermal conductive insulating composite materials in fields such as electronics and thermal management, and explores their potential applications in emerging technologies like new energy and sustainable development. Finally, it concludes by summarizing current research hotspots and future trends, emphasizing the crucial role of continuous innovation in material design and fabrication processes for driving widespread applications of such materials across various domains.

Keywords

Thermal Conductive Insulating Composite Materials; Thermal Conductivity; Insulation Performance.

1. Introduction

According to NACE's "International Measures of Prevention, Application, and Economics of Corrosion Technology" study, the global cost of corrosion is estimated at \$2.5 trillion. Various factors, including the microstructure of materials, chemical composition, and environmental conditions, collectively determine the likelihood of corrosion for specific materials and its corresponding consequences. Therefore, there has been a growing demand for research on new materials, corrosion protection, and assessment methods. In recent years, the field of materials science has seen new developments and discoveries, many of which have significantly advanced corrosion resistance and protection, thereby renewing confidence in corrosion prevention.

Epoxy resin (EP) is widely utilized due to its excellent adhesion, superior corrosion resistance, ease of copolymerization with various materials, and relatively low cost [1]. It finds extensive applications ranging from high-end sectors like aerospace and defense to civilian areas such as construction, coatings, adhesives, and beyond [2][3][4][5].

This article explores the preparation methods, performance analysis, applications, and development trends of epoxy resin thermal conductive insulation composite materials, offering a comprehensive overview of epoxy resins.

2. Preparation Method of Epoxy Resin Thermal Conductive Insulation Composite Materials

Epoxy resin thermal conductive insulation composite materials have attracted considerable attention due to their widespread applications in fields such as electronic packaging. Here is an overview of several methods for preparing such composite materials:

2.1 Al₂O₃/Epoxy Resin Composite Materials

Through gel casting, sintering, and vacuum infiltration methods, Al₂O₃ green bodies are first formed. After debinding at 600°C, they are sintered at different temperatures ranging from 1200°C to 1500°C to achieve porous Al₂O₃ ceramic frameworks with varying porosities. Epoxy resin is then vacuum infiltrated into the sintered porous Al₂O₃ ceramic framework, curing to form Al₂O₃/Epoxy Resin composite materials. This method achieves a high Al₂O₃ loading of up to 70% by volume, with flexural strength and thermal conductivity reaching 305 MPa and 13.46 Wm⁻¹K⁻¹, respectively.

2.2 Boron Nitride Nanosheet-Epoxy Resin Composite Materials

The preparation method involves ultrasonic dispersion of silane coupling agent-modified boron nitride nanosheets and ethylenediamine-modified carbon nanotubes in acetone. After adding epoxy resin and heating with stirring until acetone evaporates, methyl tetrahydrophthalic anhydride and dmp30 promoter are added. After thorough mixing, vacuum degassing is performed, followed by injection into molds for curing, resulting in thermal conductive and insulating epoxy resin composite materials.

2.3 Diamond-modified Epoxy Resin Composite Materials

The preparation method involves mixing diamond with nickel powder, sintering, and then removing the nickel powder with dilute hydrochloric acid solution to obtain modified diamond. Subsequently, the modified diamond is mixed with epoxy resin, followed by the addition of curing agent and curing to obtain the composite material. By controlling the ratio of diamond to nickel powder, composite materials with good insulation and high thermal conductivity can be prepared.

2.4 Toughened Thermal Conductive Insulation Epoxy Resin-based Composite Materials

This method involves preparing acrylic core-shell particles and modifying boron nitride particles, as well as preparing epoxy resin-based composite materials. Boron nitride microparticles are modified to the desired form by combining ball milling and liquid-phase ultrasound. These are then mixed with core-shell particles and epoxy resin, and after the addition of curing agent and promoter, the mixture is cured and shaped after centrifugal degassing, resulting in composite materials with high thermal conductivity and insulation properties.

2.5 High thermal Conductivity Insulation BN/EP Composite Materials

Using BN as filler and EP as the matrix, high thermal conductivity insulation BN/EP composite materials are prepared by enhancing the compatibility between BN and EP through surface modification. Experimental results indicate that using KH560 for surface modification of BN and with a filler content of 20% by volume, BN-560/EP composite materials exhibit a thermal conductivity coefficient 7% higher than BN-550/EP. Moreover, the hexagonal-BN crystal structure is more suitable as a high thermal conductivity filler for composite materials.[7]

3. Thermal Conductive Fillers: Selection and Application

Thermal conductive fillers, as crucial components for enhancing material thermal conductivity, play a pivotal role in various fields such as electronic packaging, LED lighting, and new energy vehicles.

3.1 Selection of Thermal Conductive Fillers

The selection of thermal conductive fillers is primarily based on their thermal conductivity, insulation performance, chemical stability, cost-effectiveness, and compatibility with the matrix material. Common types of thermal conductive fillers can be categorized as follows:

3.1.1 Inorganic Insulating Fillers

Materials such as alumina (Al_2O_3), boron nitride (BN), aluminum nitride (AlN), silicon carbide (SiC), etc. These materials typically exhibit excellent thermal conductivity and good insulation properties.

3.1.2 Metal Fillers

Materials such as copper powder, silver powder, etc. While they offer excellent thermal conductivity, they can reduce the insulation properties of the material.

3.1.3 Carbon Materials

Including graphite, carbon fibers, carbon nanotubes, and graphene, these materials not only exhibit high thermal conductivity but also possess good electrical insulation properties. Graphene, in particular, is renowned for its ultra-high thermal conductivity and excellent mechanical properties, making it highly desirable in the field of thermal conduction.

3.1.4 Composite Thermal Conductive Powder Fillers

Composed of a mixture of various thermal conductive fillers, these are designed to enhance the overall thermal conductivity performance of materials through optimized combinations.

3.2 The Influence of Thermal Conductive Fillers on the Performance of Composite Materials

The performance of thermal conductive fillers significantly impacts the properties of composite materials, primarily in the following aspects.

3.2.1 Enhancement of Thermal Conductivity

The addition of thermal conductive fillers can greatly improve the thermal conductivity of polymer matrices. For example, polymer nanocomposites achieve enhanced thermal conductivity by incorporating zero-dimensional, one-dimensional, two-dimensional, and three-dimensional nano thermal conductive fillers, thus constructing a conductive structure to increase the thermal conductivity coefficient of the composite material.

3.2.2 Utilization of Thermal Conduction Mechanisms

The type and structure of thermal conductive fillers directly affect the thermal conduction mechanisms of composite materials. Inorganic non-metallic fillers such as oxides, carbides, and nitrides, as well as carbon-based fillers like graphite, carbon fibers, and carbon nanotubes, due to their high thermal conductivity, effectively enhance the thermal conductivity performance of composite materials [8].

3.2.3 Improvement of Interface Compatibility

The interface compatibility between thermal conductive fillers and polymer matrices is equally crucial for the thermal conductivity performance of composite materials. Modifying thermal conductive fillers through surface functionalization or coating can enhance their adhesion to the matrix, reduce interface thermal resistance, and thus improve the thermal efficiency of the composite material [8].

3.2.4 Optimization of Filler Content

The amount of filler directly affects the thermal conductivity performance of composite materials. An appropriate amount of filler can build an effective thermal conductive network, whereas excessive filler may cause aggregation, thereby reducing thermal conductivity. For instance, in MgO/EPDM composite materials, the thermal conductivity increases maximally when the MgO content reaches a certain value [8].

3.2.5 Construction of Thermal Conductive Networks

Through specific preparation techniques such as ice templating and 3D printing, two-dimensional sheet-like thermal conductive fillers can be vertically oriented to form efficient thermal pathways, thereby enhancing the through-plane thermal conductivity of composite materials.

3.2.6 Expansion of Application Fields

Thermal conductive composites find significant applications in wearable electronic devices, thermal interface materials, battery thermal management, and various other fields due to their excellent thermal conductivity. The performance of thermal conductive fillers directly impacts the performance and reliability of these applications.

3.2.7 Balancing Insulation and Thermal Conductivity

In certain applications such as the integrated circuit industry, materials are required to balance insulation and thermal conductivity. Carbon-based fillers, with their unique properties such as high thermal conductivity, low density, and active surface area, demonstrate significant potential in polymer-based composite materials. However, controlling their electrical conductivity is also necessary to meet insulation requirements [9].

3.3 Enhancement of Thermal Conductive Fillers through Composite Modification and Performance Improvement

Surface modification of thermal conductive fillers is a crucial method to enhance the performance of composite materials. Through surface modification, the compatibility between fillers and polymer matrices can be improved, enhancing dispersion, reducing interfacial thermal resistance, and thereby increasing the thermal conductivity of composite materials.

3.3.1 Purpose of Modification

The primary goal is to increase the filler loading and dispersion of thermal conductive powders in resins, while imparting specific functional properties according to requirements.

3.3.2 Mechanism of Modification

Inorganic thermal conductive fillers such as aluminum hydroxide and alumina have hydrophilic groups on their surfaces, which are incompatible with typically hydrophobic and non-polar resin matrices. Surface modification treatments can improve this interface incompatibility issue, enhancing their adhesion and compatibility.

3.3.3 Modification Methods

These include surface chemical organic coating, liquid-phase chemical precipitation coating, vapor-phase physical deposition, mechanochemical methods, and layered structure powder intercalation. These methods effectively alter the physical and chemical properties of powder surfaces to meet specific application requirements.

3.3.4 Selection of Modifiers

The type and amount of modifiers significantly affect the oil absorption value, activation index, and particle size distribution of alumina powders. Experiments show that alumina powders modified with silane coupling agent CG12 exhibit lower oil absorption values and higher activation indices, capable of preparing organosilicon encapsulants with excellent comprehensive performance [10].

3.3.5 Effect of Modification

The crystal structure of modified thermal conductive fillers remains unchanged, with reduced agglomeration and improved dispersion. This enhances the thermal conductivity of composite materials and lowers viscosity, optimizing the overall material performance [10].

3.3.6 Filler Loading and Performance

Studies indicate that with increasing filler loading, the thermal conductivity and heat resistance of composite materials increase, while volume resistivity and breakdown strength decrease. Tensile strength initially increases and then decreases, while elongation at break gradually decreases.

Appropriate filler loading can enhance material performance while maintaining good flow processability [10].

3.3.7 Research Progress on Surface Modification Techniques

Surface modification techniques for thermal conductive fillers are currently a hot topic in materials science research. New modification technologies and methods are continuously being developed to meet the increasing demand for high-performance composite materials.

4. Applications of Epoxy Resin Thermal Conductive Insulation Composite Materials

4.1 Electronic Packaging Field

Electronic packaging technology involves the protection and thermal management of chips and electronic devices, directly impacting equipment performance and reliability. As electronic devices trend towards integration and miniaturization, effective thermal management becomes crucial. Epoxy resin, due to its excellent electrical insulation, chemical stability, and good mechanical properties, has become one of the preferred materials in the electronic packaging field. In electronic packaging, epoxy resin is typically used as bottom filling material to fill gaps between flip chips and substrates, dispersing thermal stress at solder joints and providing physical protection. With the increasing heat power density of integrated circuit chips, effective heat dissipation becomes essential for the stability and reliability of electronic equipment.

4.2 Thermal Conductive Potting Field

Potting protects electronic components from moisture, pollution, and physical damage, while providing necessary heat conduction paths. Using high thermal conductive insulation epoxy resin composite materials can effectively enhance the heat transfer efficiency of electronic products and maintain stable operation. In practical applications, thermal conductive potting compounds are mainly used in electronic component encapsulation and precise component potting sealing fields. For instance, by using high thermal conductive gel for overall potting of motor stators, air gaps in the stator slots can be eliminated, and the thermal conductivity of the insulation system itself can be improved. This is crucial for improving equipment reliability and extending its service life.

It is worth noting that the application of epoxy thermal conductive potting compounds is not without challenges. In practical operations, issues such as excessively long curing time, bubbles appearing on the surface after curing, or the phenomenon of soft gels may occur. Therefore, optimizing construction processes, strictly controlling ratios, and curing conditions are crucial to ensuring the performance of the final product.

4.3 Metal Substrate Clad Copper Plate

Metal substrate clad copper plates are critical materials in the fields of electronics and electrical engineering, demanding stringent performance requirements for thermal conductive insulation composites. They need to possess high thermal conductivity to effectively transfer heat while maintaining excellent electrical insulation properties. Through research on key technological issues such as surface modification of fillers, blending, liquid crystal epoxy application, and orderly configuration of electric field-regulated fillers, the comprehensive performance of epoxy resin composite materials continues to be enhanced. High thermal conductivity epoxy resin-based composite insulation materials have broad prospects in metal substrate clad copper plates, particularly in addressing the thermal dissipation challenges brought by electronic equipment miniaturization and integration, thus holding significant value.

4.4 Motor Applications

Due to their excellent electrical insulation properties, such composite materials are widely used in motor insulation systems. They maintain superior mechanical and electrical performance even under high-temperature operating conditions, ensuring motor reliability and stability. Moreover, the

extensive application of high thermal conductivity epoxy resin composite materials effectively enhances the thermal conductivity of motor insulation systems, reduces motor temperature rise, improves reliability and stability during motor operation, and ensures the safe operation of the system.

5. Trends of Epoxy Resin Thermal Conductive Insulation Composite Materials

5.1 Innovation in Preparation Technology

Surface modification techniques play a crucial role in enhancing the compatibility between epoxy resin and fillers, optimizing interface bonding, and effectively improving the thermal conductivity of composite materials. Precise control over filler distribution and size further optimizes the thermal conduction network, enhancing thermal efficiency. Compared to nano-sized boron nitride, micron-sized boron nitride is more effective in enhancing thermal conductivity.

Current research primarily focuses on filled thermal conductive epoxy resin composites, which establish effective thermal paths by incorporating high thermal conductivity fillers. Commonly used thermal fillers include boron nitride (BN), alumina (Al₂O₃), and aluminum nitride (AlN). Particularly, hexagonal boron nitride (h-BN), with its large particle fillers possessing high thermal conductivity and good wettability, can blend well with smaller particles to form more effective thermal networks, demonstrating optimal thermal conductivity.

To further enhance the thermal conductivity of composite materials, researchers have explored multi-component and high-content filler combinations. For instance, adding a small amount of silver nanowires (AgNWs) to h-BN modified composites can further increase the material's thermal conductivity while maintaining good electrical insulation. This approach not only enhances thermal performance but also ensures reliability and safety in practical applications.

5.2 Expansion in Application Areas

With increasing demands for heat dissipation in the electronics industry, epoxy resin thermal conductive insulation composite materials are finding wider applications in electronic packaging, high-density integrated circuits, power electronics, and other fields. Research on their application in low-temperature environments, particularly as insulation materials in superconducting technology, requires excellent low-temperature resistance and good thermal conductivity. There are also further expansions in areas such as power modules, LED lighting, automotive electronics, where the application of high thermal conductive epoxy resin composite materials can enhance thermal management of power products, ensuring stable operation under high power density conditions.

5.3 Challenges and Opportunities in Sustainable Development

Increasingly stringent environmental regulations require thermal conductive insulation composite materials to meet environmental standards during production and use, posing challenges to the sustainable development of these materials. Developing new environmentally friendly materials, reducing energy consumption and emissions during production, and exploring more eco-friendly raw materials and manufacturing processes will be key focuses of future research.

5.4 Development of Multifunctionality

In addition to thermal conduction and insulation, future epoxy resin composite materials need to possess additional functionalities such as flame retardancy, high mechanical strength, and resistance to chemical corrosion to meet more complex application environments.

5.5 Cross-Disciplinary Technological Integration

By integrating modern nanotechnology and surface treatment techniques across different fields, novel thermal conductive insulation composite materials with superior performance and broader application scope can be developed.

Acknowledgments

Supported by the Provincial Undergraduate Innovation and Entrepreneurship Training Program (S202310081145).

2023 Undergraduate Innovation and Entrepreneurship Training Program of North China University of Science and Technology (T2023063).

References

- [1] Shang Beirong, Qi Rong, Qi Heat Hua. Progress on epoxy-based thermal insulating composites [J]. Adhesive, 2016,37 (11): 26-30.
- [2] Liu Fuhua. Synthesis of carboxyl side group and its modified epoxy resin as a macromolecular curing agent [D]. Dalian University of Technology, 2009.
- [3] Li Shuang. Synthesis of functional siloxane and its modified epoxy resin [D]. Hubei University, 2019.
- [4] Wang Runting. Synthesis and curing behavior of imidazole reactive diluent [D]. Beijing University of Chemical Technology, 2019.
- [5] Yueh Sun. Study on properties of modified epoxy siloxane [D]. Zhejiang University, 2019.
- [6] Yong Hu, Guoping Du, Nan Chen, A novel approach for Al₂O₃/epoxy composites with high strength and thermal conductivity, Composites Science and Technology, Volume 124, 2016, Pages 36-43, ISSN 0266-3538, <https://doi.org/10.1016/j.compscitech.2016.01.010>.
- [7] Wang Hebing. Preparation and properties of epoxy resin matrix composite with high thermal conductivity [D]. Harbin University of Science and Technology, 2019.
- [8] Yu Liyuan, Yang Dan, Wei Qungui, et al. Progress of filled polymer thermal conductivity composites [J]. Rubber Industry, 2020,67 (11): 873-879.
- [9] Tian Fear Hu, Wu Yang, Sheng Shaoding, etc. Progress of carbon-based packing in polymer-based insulating thermal conductivity composites [J]. Journal of Composite Materials, 2021,38(04):1054-1065. DOI:10.13801/j.cnki.fhclxb. 20201224.001.
- [10] Zhao Dengyun. Research on the surface modification of high thermal conductivity fillers and its application [J]. [2024-07-14].